OBSERVATIONS ON DEGRADATION OF UV SYSTEMS ON NIMBUS SPACECRAFT

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GSFC —— GODDARD SPACE FLIGHT CENTER ——
GREENBELT, MARYLAND

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ABSTRACT

Broad band photometer experiments in the 1200 to 3000A have been operating on Nimbus 3 and 4 since April 1969 for the purpose of determining the nature of variations in the uv solar irradiance. An Ebert-Fastie double monochromator has been measuring the solar irradiance and earth radiance from 2500 to 3400A for the determination of global atmospheric ozone distributions since April 1970. From pre-launch testing and an evaluation of the flight data it is concluded that the principal source of degradation is probably the spacecraft. The degradation produces a characteristic signal loss and change in angular response of the system which might be explained by micron sized droplets becoming a permanent residue under the influence of solar uv radiation.

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INTRODUCTION

The launch of an ultraviolet radiation experiment aboard an earth orbiting satellite places it into a very hostile environment which is especially severe if small changes in uv radiation levels are to be observed over periods of months or years. This is critical if one is looking for changes in the solar-terrestrial radiation system which may be indicative of long term climatological changes. In the coming years one will be faced with assessing the nature of the problem associated with the pollution of the stratosphere and its relationship to man and his environment. This work is concerned with observations on the nature of degradation in uv systems which were designed for nominal one year operational lifetimes on Nimbus 3 and 4 for the investigation of the uv solar-terrestrial radiation system.

Some possible sources of degradation which one should consider are: the trapped charged particle radiation belts particularly in the vicinity of the South Atlantic Anomaly, outgassing from the spacecraft, solar radiation which produces both thermal effects and uv induced photochemical changes, and micro-meteorite impacts on optical surfaces.

The observations on the space degradation of uv systems which are described in this paper were derived from one experiment on Nimbus 3 and two on Nimbus 4. The Nimbus 3 and 4 spacecraft, earth oriented, were put into circular, 10° retrograde (near polar), sun synchronous orbits at an altitude of 1100 km in April 1969 and April 1970 respectively. The spacecraft traverse the ascending node of the orbit near local noon. The location of the experiments is such that they are subject to a changing angle of solar illumination from about 45° from the daylight side of the terminator through the passage into satellite night which occurs about 30° past the terminator.

The Monitor of Ultraviolet Solar Energy (MUSE) experiment was flown on Nimbus 3 and 4. Its objective was to investigate the magnitude and types of variability of the solar irradiance in relatively broad spectral bands in the 1200 to 3000A region which is important for meteorology. The MUSE experiment on Nimbus 3 was operated continuously from launch in April 1969 until the spacecraft was deactivated in January 1972. This experiment on Nimbus 4 has operated continuously since launch in April 1970.

The BUV, Backscatter Ultraviolet, experiment on Nimbus 4 consists of a double monochromator of 0.25 meter focal length which is basically a tandem

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Ebert-Fastie type. The BUV measures: the earth radiance and solar irradiance at 12 wavelengths (10A bandpass) from 2550 to 3400A and at 3800A with a 50A bandpass photometer channel. This experiment recently completed 12,000 orbits of operation in September 1972.

The MUSE and the BUV experiments were the sources for the observations which are discussed in this work. The principal objectives of this work were to determine:

(a) The principal source of degradation in uv space optical systems.

(b) The temporal character of the system degradation.

A knowledge of the above should help in the design of future experiments and in the analyses of the observations to separate slowly varying solar-terrestrial radiations from system changes.

INSTRUMENTS

A MUSE sensor package is shown in Figure 1 which is located in the Nimbus sensory ring 180° from the velocity vector. The five broad band photometer channels have a nominal 90° field of view and are illuminated at near normal incidence over the northern terminator. A digital solar aspect sensor located in the upper section of the sensor package provides the angle of solar illumination of the sensors at 0.7° increments. The passband of a photometer channel is determined by the short wavelength cut-off of uv transmitting materials and the long wavelength rejection of different "solar blind" photocathodes.

A functional diagram of the BUV experiment is shown in Figure 2. The optical path of the earth radiance from a 12° field of view traverses a Al_2O_3 particle radiation shield, a double-Lyot calcite depolarizer, two Ebert mirrors, the first coated with a multi-layer coating of Al and MgF_2 (peaked at 2500A) and the second with Al, two Al coated replica gratings, high purity fused silica transfer prisms and field lenses in the path through the double monochromator to the Al_2O_3 window of the photomultiplier. At the northern terminator a diffuser plate of ground Al and overcoated with pure vacuum deposited Al is deployed for measurement of the solar irradiance. The diffuser plate is illuminated at an angle of 55° to the normal when the solar vector lies in the plane of the optic axis and the diffuser plate normal. The diffuser plate is exposed at all times to space and solar radiation in the vicinity of the northern terminator. When the plate is in the stowed position, light baffles restrict the instrument field to 12° of the terrestrially scattered solar radiation.

Figure 1. MUSE Experiment Sensor Package with Five Sensors and Digital Solar Aspect Sensor at the Top

More complete descriptions of the instruments may be found in the Nimbus 3 and 4 User Guides.

OBSERVATIONS

Degradation in Response

Prior to the fabrication of the MUSE experiment it was felt that the most likely source of degradation in a uv optical system operating in the planned Nimbus orbit would be the high energy trapped particle radiation environment. High energy electrons in the MeV energy range can degrade uv optical materials through the formation of color centers which shift the short wavelength transmission limit to longer wavelengths. The color centers can be formed by either direct ionization produced as the electron loses energy in its passage through the material or by the bremsstrahlung produced by the collision between the electron and a surface. The resulting high energy photons subsequently produce ionization in their passage through the optical materials.

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SPHERICAL COLLIMATING MIRRORS

NADIR   OUTBOARD

PHOTOMETER SLIT

GRATING

PLANE PRISM

PHOTOMETER CALIBRATION SOURCE (CERENKOV)

FIELD LENS

REFERENCE SOURCE MIRROR

INTERFERENCE FILTER

EXIT SLIT

EXIT LENS

ROOF PRISM

PLANE MIRROR

WAVELENGTH CALIBRATION SOURCE

PHOTOMETER PHOTOMULTIPLIER TUBE

GRATING

ENTRANCE SLIT

AUXILLARY SLIT

MONOCHROMATOR PHOTOMULTIPLIER TUBE

REFERENCE SOURCE MIRROR

PHOTOMETRIC CALIBRATION SOURCE

PHOTOMETER INPUT

DEPOLARIZER

MONOCHROMATOR INPUT

12°(TYP)

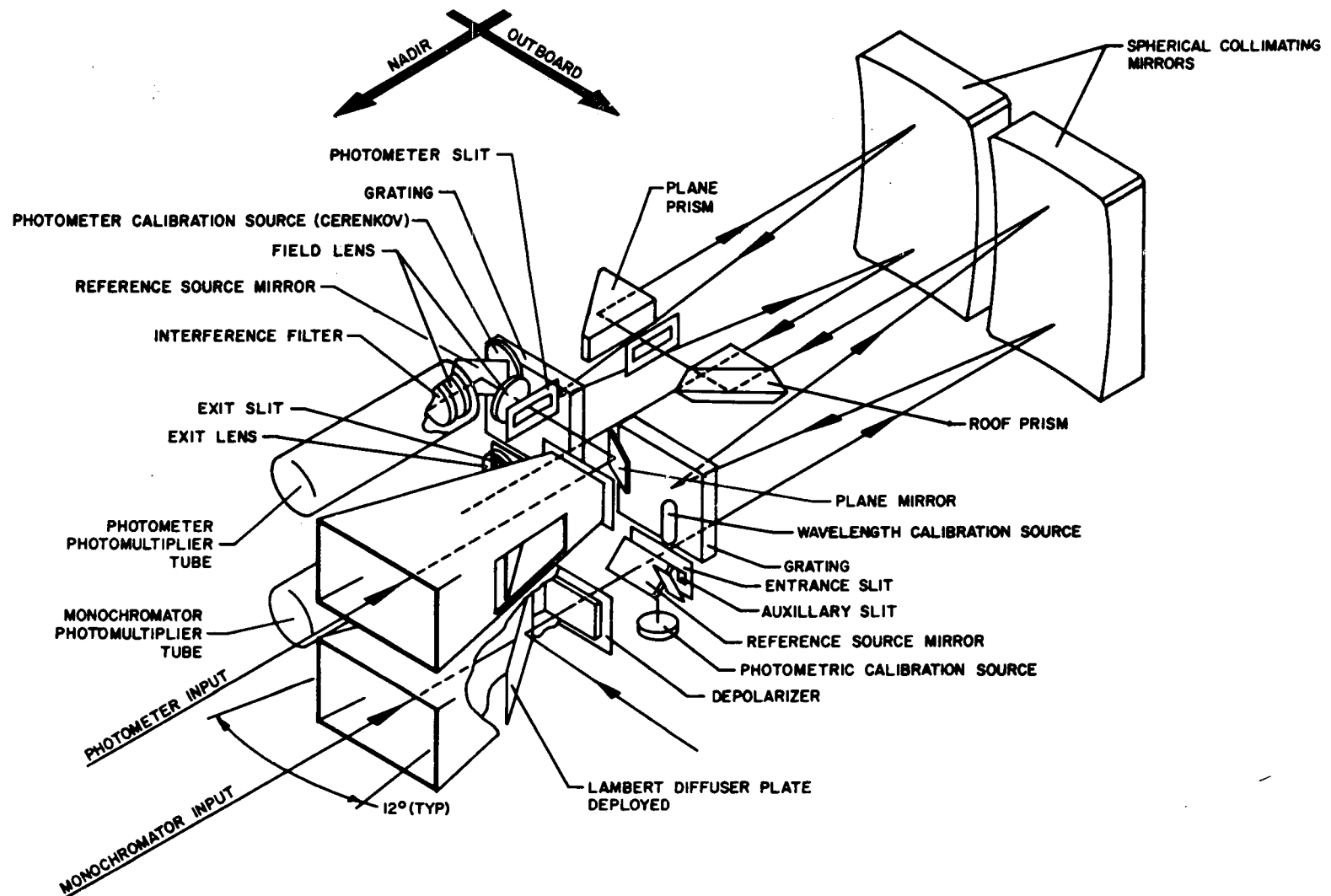LAMBERT DIFFUSER PLATE DEPLOYED

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Figure 2. Optical Component Diagram of Nimbus 4, BUV Experiment

An estimate of the anticipated charged particle flux that Nimbus 3 would encounter in one year was 10^{13} e$^-$/cm^2 at an equivalent energy of 1 MeV which gives an energy deposition of about 2×10^7 ergs/cm^2 yr as an upper limit. A series of investigations on the effect of 1 to 2 MeV electrons on uv transmitting materials, Heath and Sacher (1966), and uv photocathodes (Heath and McElaney (1968) at 10^{14} e$^-$/cm^2 indicated that the effects on MUSE and BUV experiments should be negligible at the end of one year in space. Corresponding degradation studies with protons indicated their contribution to degradation in the Nimbus orbit would be trivial (Heath, MeElaney and Sacher, unpublished work).

Some recent results on the effect of increasing doses of high energy electron irradiation on the transmittances of LiF and MgF$_2$ are shown in Figure 3. The transmittance is proportional to the logarithm of the dose. (Heath and Fedor, to be published.) The multiple straight line segments may indicate possible saturation effects although admittedly there are too few data points.
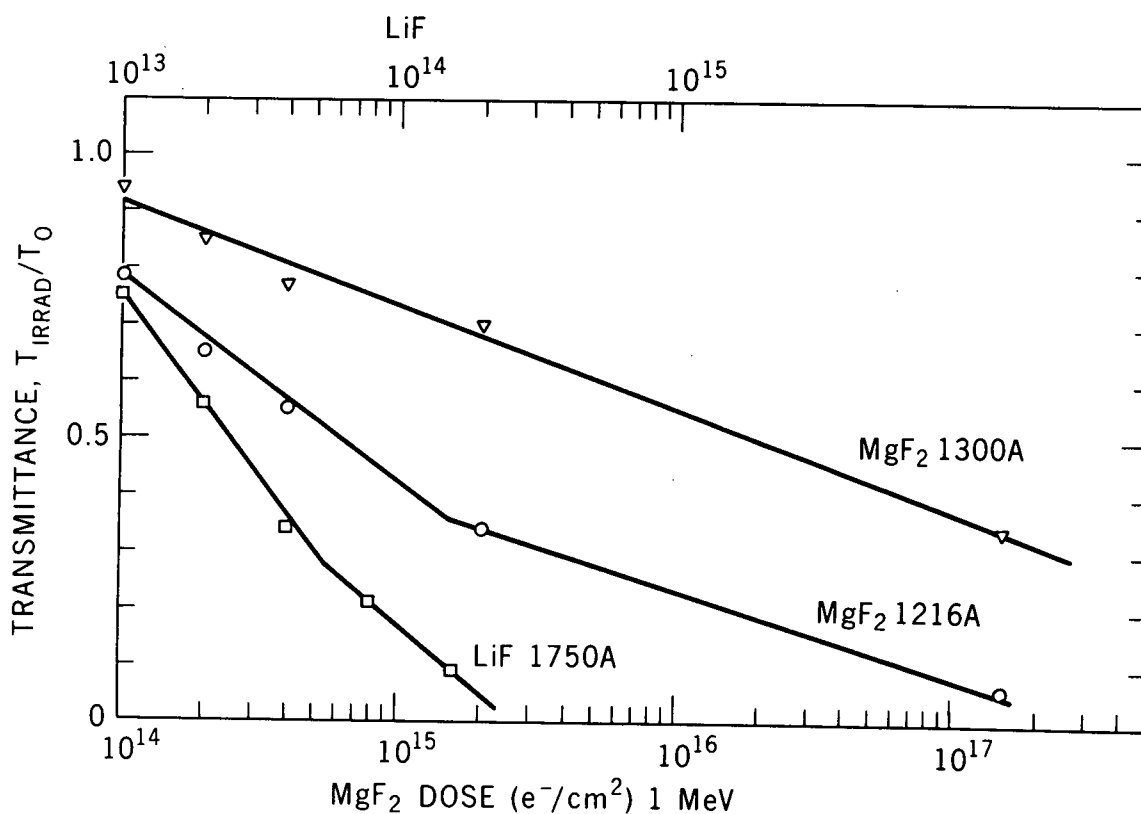

Figure 3. Change in Transmissions in LiF and MgF$_2$ with Increasing Doses of 1 MeV Electrons

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The actual signal decay curves for two of the MUSE sensors on Nimbus 3 are shown in Figure 4. The sensor with the MgF_2 window and W photocathode responds principally to H Lyman alpha and exhibits an initial decay period (e^{-1}) of 77 days for the period between day 100 and 230 in 1969. The secondary period characteristic of the signal after day 230 is 284 days. The other sensor consisted of a MgF_2 outer particle shield and vacuum photodiode using a semi-transparent CuI photocathode deposited on a CaF_2 window. Since both sensors use MgF_2 as the element exposed to space, the most likely source of degradation is H Lyman alpha which is absorbed in the CaF_2 window. Considering that the sensor is illuminated for about 20 minutes for each 107 minute orbit, the transmittance of the outer MgF_2 element, and the solar irradiance at H Lyman alpha, the rate of Lyman alpha energy absorption is about 1×10^7 ergs/cm^2 yr. The observed initial decay period is 0.12 days. The secondary period is 14.4 days and the tertiary period is 43.7 days. For both of these sensors the logarithm of the signal is a linear function of time with negative slope over particular time intervals.

A composite of 30-day signal averages of sensors common to Nimbus 3 and 4 which have been corrected for the annual variation of earth-sun distance is shown in Figure 5. The signals have been averaged over 30 days to smooth the 27-day variations which are associated with the solar rotational period. In general the logarithm of the sensor signal is a linear function of time with negative slope over specific time intervals, and furthermore the slopes are a decreasing function with increasing time. This characteristic which can be associated with saturation phenomena has been used to infer times when actual changes in the solar irradiance may occur.

For example, this has led to the conclusion that there was an overall increase in the irradiance at Lyman alpha which peaked in the spring of 1969 and 1971. This is indicated in sensors A. There is also an indication from sensor B on Nimbus 3 of a significant change in the solar irradiance at 1750A towards the end of 1969.

A summary of the sensor degradation observed in the MUSE experiments is given in Table 1. It should be noted that on board electronic calibrations and the fact that all sensors are switched into a common electrometer make it very unlikely the signal decrease with time can be attributed to an electronic malfunction. On Nimbus 4 sensor A which responds to Lyman alpha, experienced a degradation which was one-third that observed on Nimbus 3; however, sensor B (1750A) degraded by a factor of 12 more on Nimbus 4. For sensor C (2900A) the results were comparable. The factor of 2.6 increase of signal of the 2100A sensor is attributed to the increase in leakage in the side bands of the interference filter. This same effect probably would not be observed with the 2800A
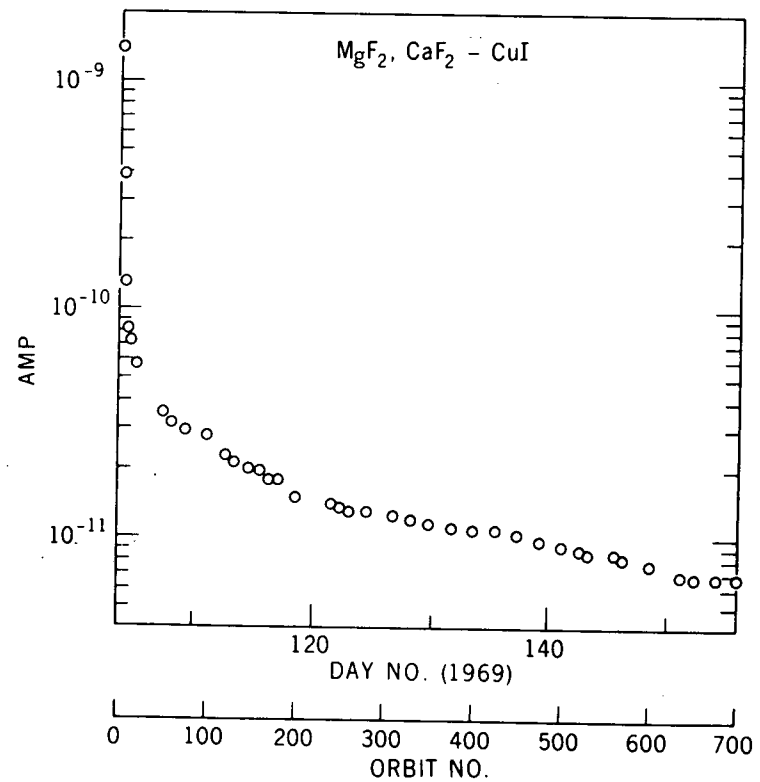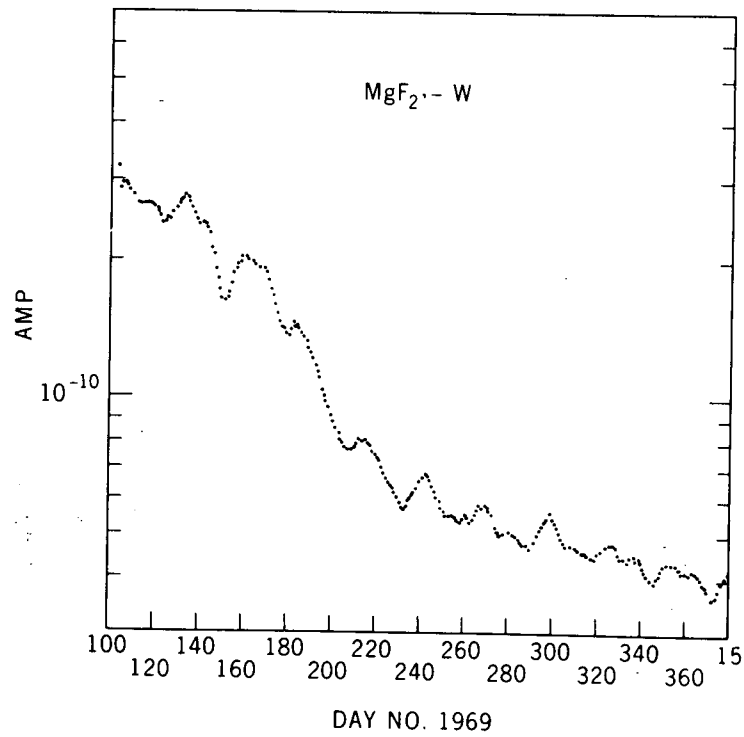
Figure 4. Probable Radiative Induced Change in Transmittance of CaF$_2$ Induced by Solar H Lyman Alpha and Satellite-Space Environment Induced Changes in the MgF$_2$ - W Sensor which Responds Principally to Solar H Lyman Alpha
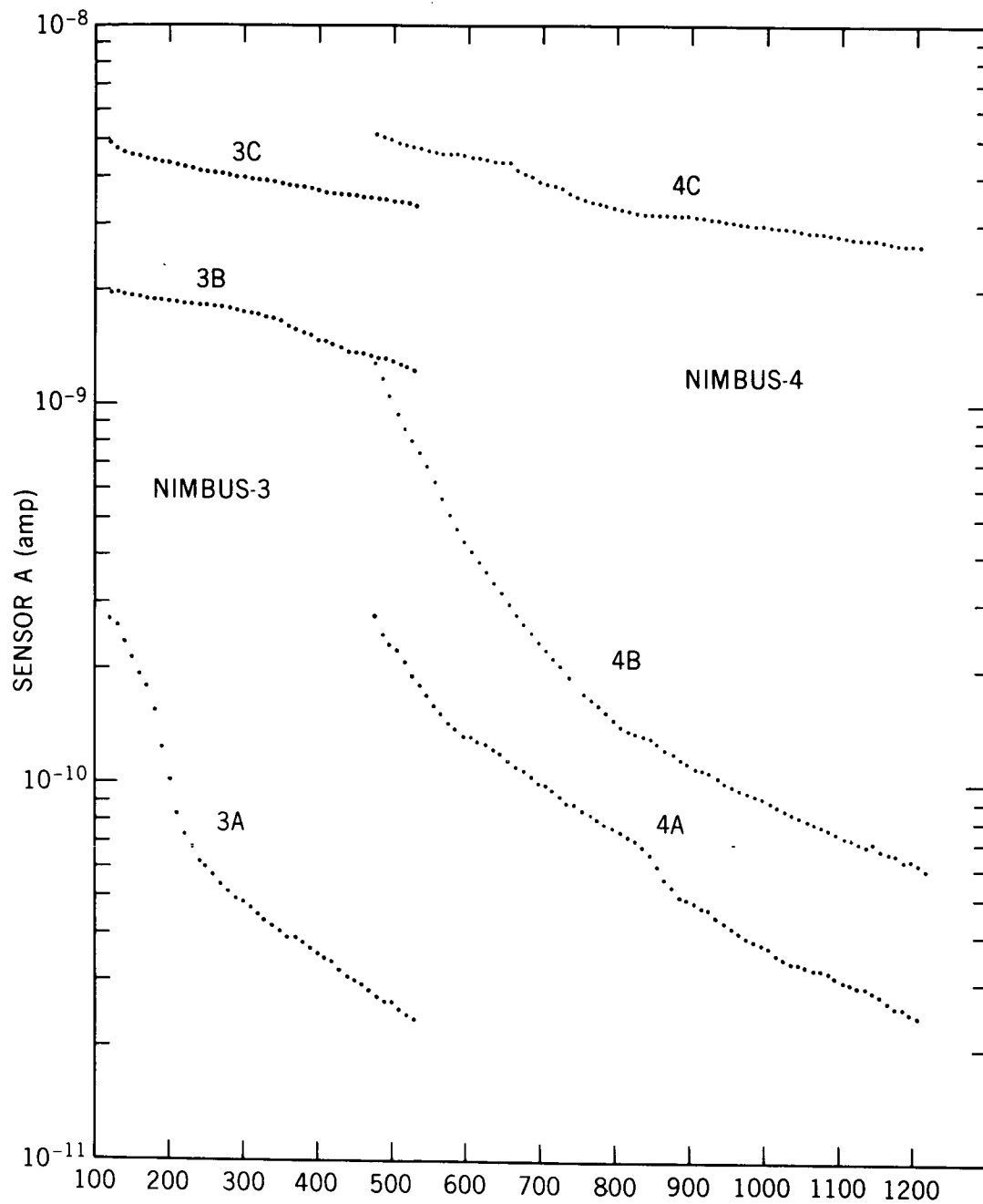
Figure 5. Summary of MUSE 30-day signal averages showing change with time for the three sensors common to Nimbus 3 and 4. Signals have been corrected for changing earth-sun distance.

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Table 1

Summary of Long Term Signal Changes in MUSE Sensors on Nimbus 3 and 4

Nimbus 3					
Sensor Signal Ratio	1216A	1750A			2900A
Orbit 11158/3 Apr. '69 – July '71	0.017	0.40			0.52
Nimbus 4					
	1216A	1750A	2100A	2800A	2900A
Orbit 12111/5 Apr. '70 – Sept. '72	0.056	0.034	2.59	0.95	0.434

sensor since it most likely would occur at a wavelength where the photocathode quantum efficiency was sufficiently low to make its contribution negligible.

The BUV experiment observations at 12 wavelengths (2550-3400A) with the double monochromator and at 3800A with the filter photometer are of two types. These are direct measurements of earth radiance and measurements of the solar irradiance at the northern terminator from a ground aluminum diffuser plate which had been overcoated with vapor deposited aluminum. An Al_2O_3 high energy particle radiation shield was placed at the entrance slit of the double monochromator. In addition, extensive laboratory testing of the diffuser plate was done in vacuum and subjected to uv, high energy electrons and protons. There were no indications of any degradation having occurred.

The observations of the solar irradiance which have been normalized to orbit 32 when the BUV was turned on are shown in Figure 6. The time interval spans 1.8 years and it is apparent that the degradation is an increasing function of decreasing wavelength.

The decrease of the solar irradiance signal at 2557 as a function of time is shown in Figure 7. As observed with the MUSE sensors, the logarithm of the signal is a linear function of time which is characterized by a negative slope which decreases in magnitude with increasing time intervals.
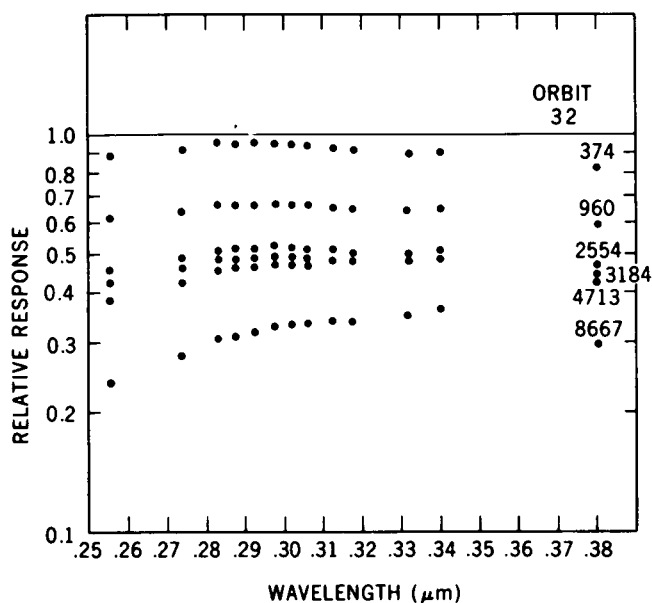
Figure 6. Apparent change in solar irradiance from
Nimbus 4, BUV observations of solar illuminated
diffuser plate at northern termination. Signals
are normalized to the experiment turn-on orbit
no. 32.

Over this same time interval one has measurements of the equatorial ter-
restrial radiance which should exhibit good long term stability if the photo-
chemistry of ozone remains constant in the equatorial upper stratosphere. The
BUV equatorial observations, uncorrected for the changing earth-sun distance,
are shown in Figure 8. The equatorial terrestrial radiance above 2976A is
strongly influenced by clouds and surface albedo. One easily can see a gradual
decrease with time of the apparent radiance and also the detector gain which was
determined by independent means. The long term changes in the apparent equa-
torial radiances are given in Table 2 for those wavelengths which originate
principally above the cloud levels. Also given are values for the corresponding
solar irradiances which were recorded with the diffuser plate. Knowing that the
total ozone has been shown to have no correlation with the 11 year sunspot cycle
and that the earth radiance which is most strongly influenced by the total amount
of ozone is in the 2900-3000A range one may conclude that in the vicinity of
3000A the long term change in signal may be explained by a slowly decreasing
gain of the detector with time. On the other hand, the equatorial radiance at
2557A is indicative of a decreasing amount of upper stratospheric ozone with
time past solar maximum. The decrease of ozone in the upper stratosphere is
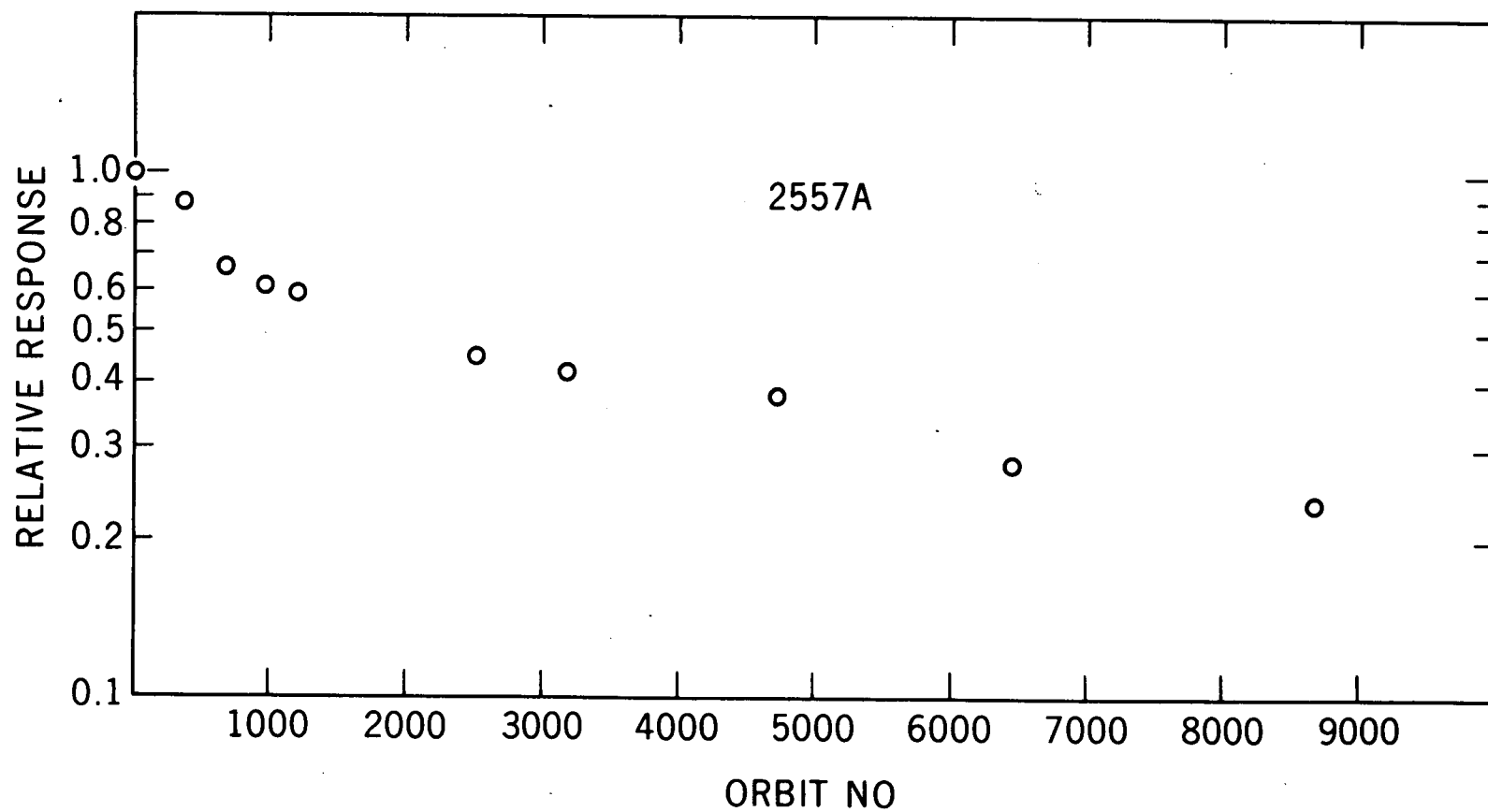associated with an increase in atmospheric radiance.

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Figure 7. Relative Change in BUV Experiment 2557A Signal from Solar Illuminated Diffuser Plate with Nimbus 4 Orbit Number
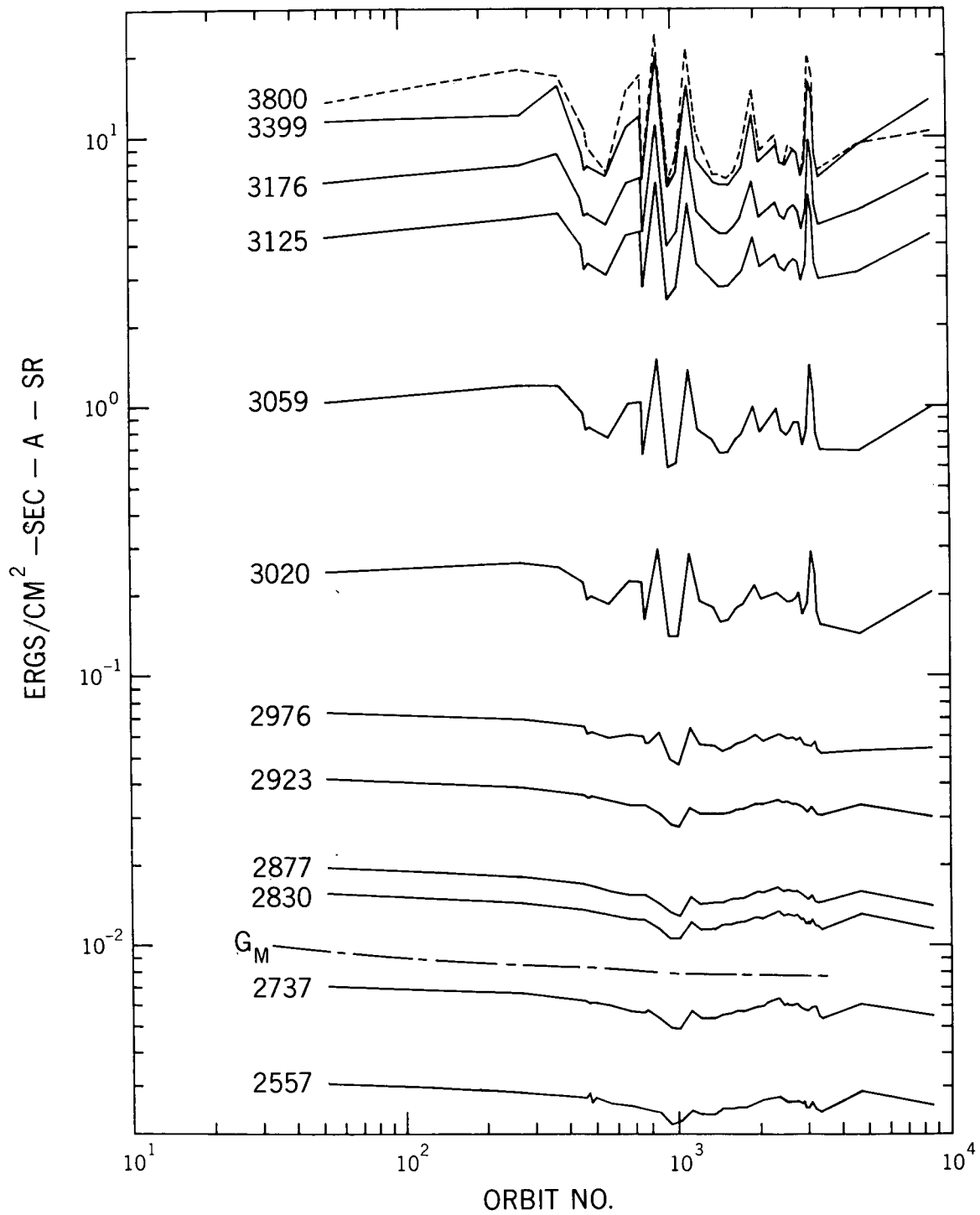
Figure 8. Summary of equatorial radiances from the vicinity of 200°W longitude based on pre-launch absolute calibration of BUV experiment. Also shown is normalized detector gain curve (G$_m$) derived from simultaneous pulse counting and current measurements.

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Table 2

Summary of Long Term Changes in BUV Experiment Observations of
Equatorial Atmospheric Radiances which Originate Above the Cloud Levels,
and Corresponding Solar Irradiances with the Diffuser Plate

Equatorial Radiance							
Ratio	2557A	2737A	2830A	2877A	2923A	2976A	Gain
Orbit 8667/32 Apr. '70 – Jan. '72	0.95	0.85	0.83	0.82	0.82	0.73	0.76
Solar Irradiance (Diffuser Plate)							
	0.24	0.28	0.31	0.31	0.32	0.33	

To a first approximation one may conclude that the monochromator signals are decreasing at a rate which may be explained by the changing gain in the photomultiplier. At the same time it appears that a very real decrease in the total reflectance of the diffuser plate is being observed.

Changes in Angular Response

The changing angle of solar illumination of the Nimbus spacecraft in its sun synchronous, local noon orbit provides additional data for the investigation of the observed degradation. The angular scan for the three MUSE sensors for orbits 101 and 10502 which spans 2.2 years is shown in Figure 9. Sensor A has a MgF_2 window and an opaque tungsten photocathode whereas sensors B and C have identical outer Al_2O_3 particle radiation shields and semi-transparent photocathodes deposited on Al_2O_2. The median sensor responses are at 1216A, 1750A, and 2950A respectively. The ordinate is a normalized sensor current divided by the cosine of the angle of solar illumination to the sensor normal. The post terminator angular response is given only for sensor C since it exhibited the largest asymmetry in angular response. The asymmetry is in the form of an azimuthal variation in angular response for a constant angle of incidence. The combination of a semi-transparent photocathode, the cathode vapor deposition technique, and the diode mechanical design all combine to produce a small secondary cathode on a wall.
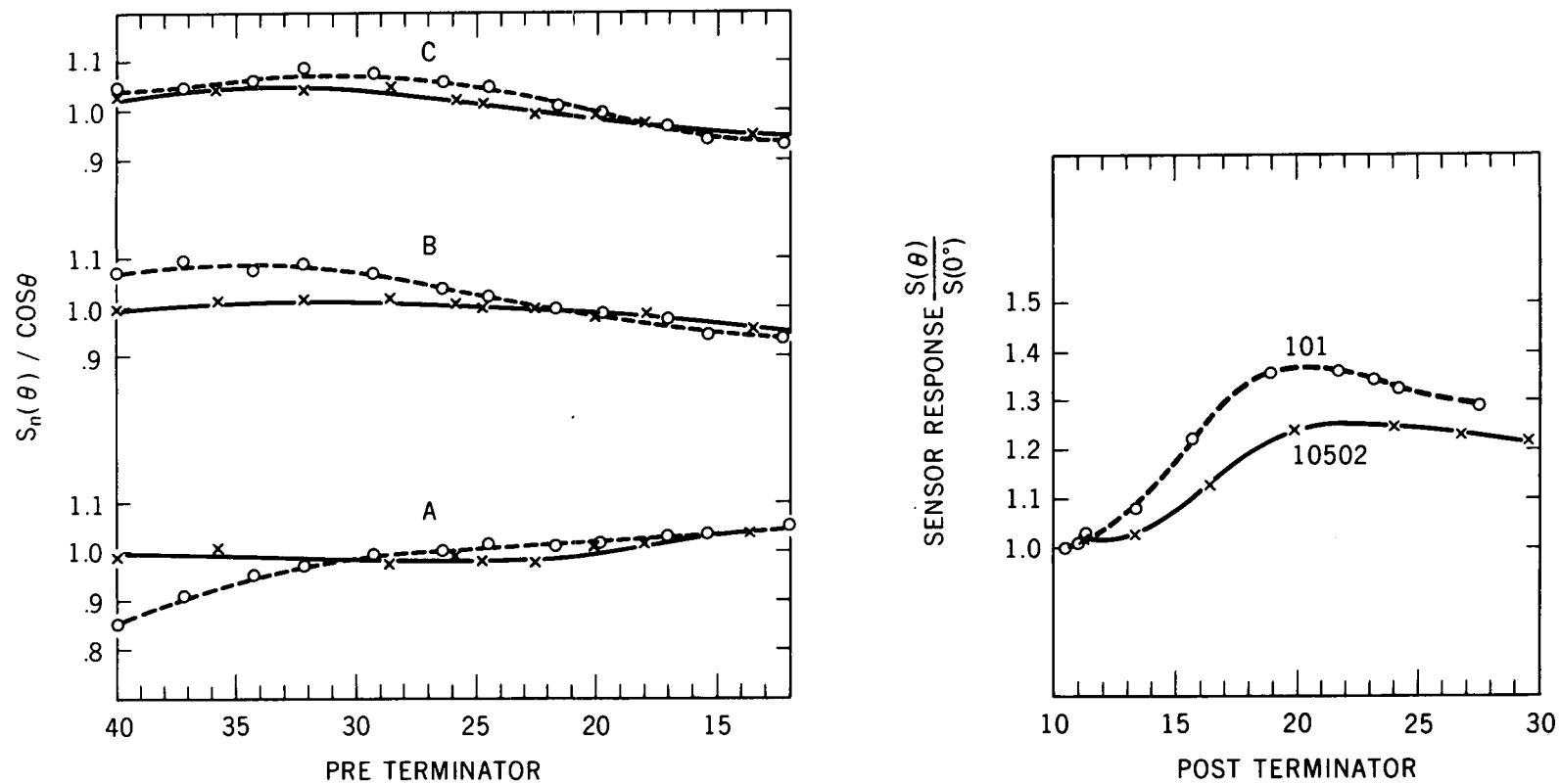
Figure 9. Change in angular response of MUSE sensors on Nimbus 3 for orbits 101 and 10,502. The angle of solar illuminations of the sensor normal at the terminator is $+3°$ for these orbits. Ordinate is the observed sensor current/terminator sensor current $\times \cos \theta$.

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The anode ring has two side holes; however, only one was used in the cathode processing which resulted in a secondary cathode being deposited onto the opposite wall which is electrically connected to the semi-transparent cathode on the front window. This effect was quite significant in the post terminator response for sensor C. The significant feature illustrated in Figure 9 is that the sensors are tending towards a cosine response with increasing time.

Changes have also been observed in the angular response of the diffuser plate in the BUV experiment with the passage of time. The angular response of the diffuser plate was calibrated in the instrument prior to launch which is shown as a straight line in Figure 10 for 3398A. The deviations from the pre-flight calibration are shown for orbits 492 and 8908 where the diffuser plate was deployed for the entire orbit. The x's labeled L represent the case of an ideal Lambertian diffuser. There is a definite indication that the ground aluminum diffuser plate is losing some of its specular component which was present in its pre-launch calibration and is tending towards a Lambertian response.

DISCUSSION

There is considerable evidence from both flight and laboratory experiments to support the contention that outgassing from spacecraft materials is a primary cause of degraded performance in satellite borne optical instrumentation. Cothran et al. (1971) have reviewed laboratory and flight test data pertaining to this problem and have documented a number of interesting cases. Reduction in transmittance of some Gemini and Apollo windows, for example, was observed by the astronauts on board and was later attributed to the outgassing of an RTV silicone elastomer used for a window sealing. McKeown and Corbin (1970) used quartz crystal microbalances aboard OGO-6 (whose orbital environment is comparable to that of Nimbus 3 and 4) to demonstrate that solar panels baking out in the sun outgassed onto the spacecraft. Their estimates of contaminant desorption activation energy identified epoxies and vacuum oils as likely suspects.

Flight instrumentation need not view solar panels to become contaminated since the opportunities for self-contamination are numerous. An investigation of the particle dynamics associated with the return and deposition of outgassed products onto critical surfaces has shown that spacecraft self-contamination is quite possible, either in flight or during vacuum chamber testing (Scialdone 1972).

Condensates may form in a variety of ways and at different rates depending on such factors as varying substrate temperatures, molecular weights, ambient pressure, time in sunlight and sputtering loss caused by upper atmospheric neutral impacts. They have been observed to condense as small droplets which
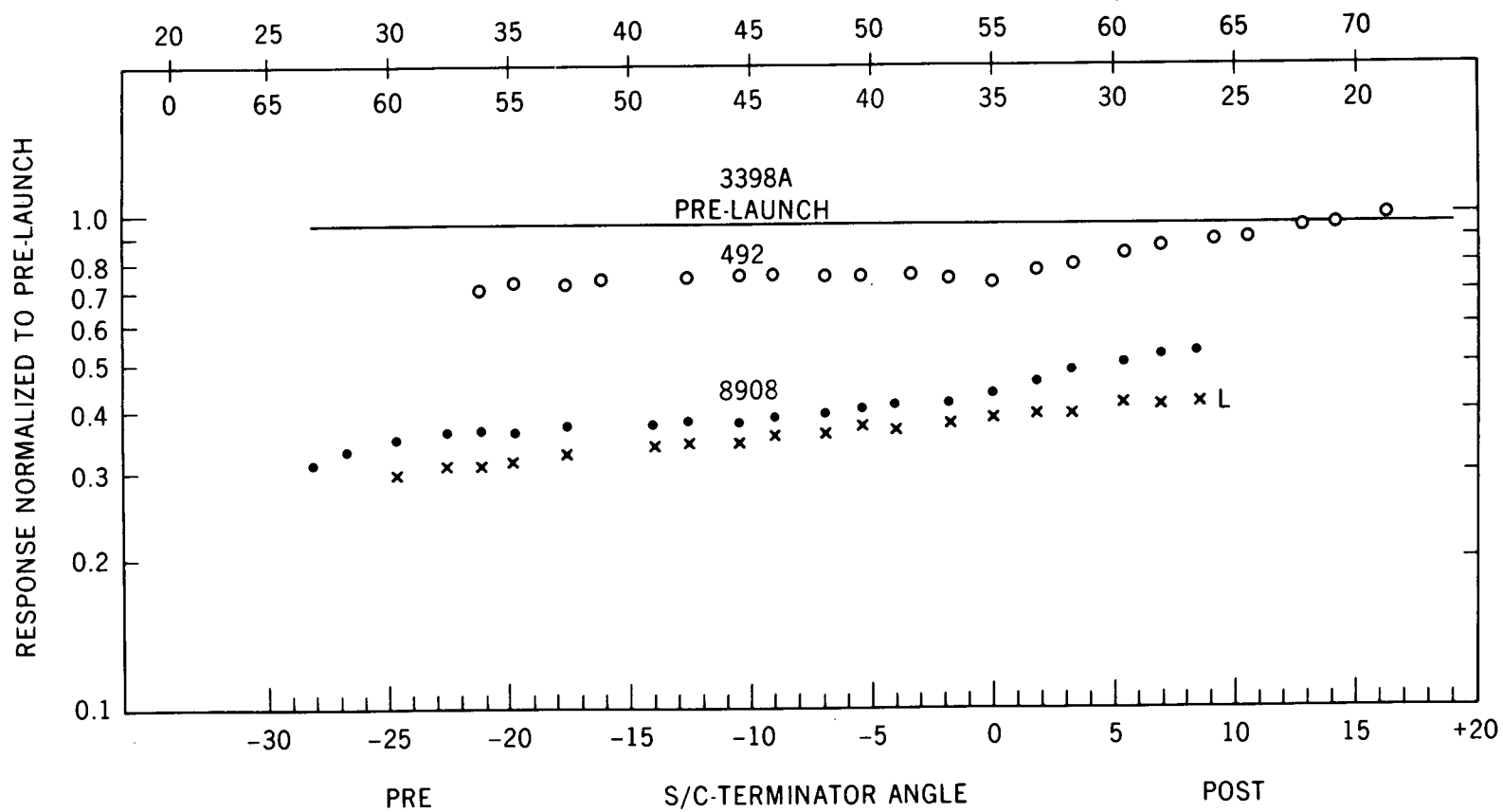
Figure 10. Change in angular characteristics of the diffuse reflectance of the BUV diffuser plate with time in orbit. The x's represent a Lambertian diffuser.

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Shapiro and Hanyok (1968, 1970) in their tests found to be 1-5 μm in diameter. These droplets eventually evaporate in the vacuum of the test chambers. However, Hass and Hunter (1970) have shown that irradiation of oil contaminated mirrors with uv, electrons, or protons, is sufficient to make the contaminant residue permanent.

Most common contaminants, such as high molecular weight organic materials, are quite transparent prior to photolysis and their presence on an optical window may not be detected by an untrained observer or in a routine transmittance measurement. The chemical decomposition induced by exposure to energetic photons, electron and protons alters this situation by creating products which absorb strongly, especially in the short wavelength regions in which the MUSE sensors operate. Even a few monolayers of a strongly absorbing surface film is sufficient to drop the transmittance of a window at Lyman-α by a factor of 10 or more.

The wavelength dependent nature of optical surface degradation in space was clearly demonstrated by the ATS-3 Reflectometer Experiment (Heaney 1970). Highly specular mirror surfaces that experienced a drastic reduction in reflectance in the 300-400 nm spectral region showed little or no loss for wavelengths longer than 650 nm. The loss of specular reflectance, although large at first, tended to saturate with time over a 2 year period. These observations are consistent with the MUSE data and suggest a common mechanism.

Evaporated aluminum surfaces flown on the ATS-3 reflectometer suffered a loss of reflectance that was linear with time and did not exhibit the same tendency toward saturation as those mirror surface with dielectric overlayers. Since only the specular component of reflectance was monitored, it is not possible to say with certainty that the mirrors were being roughened. The data does support this interpretation, however, and is quite consistent with the change in angular reflectance exhibited by the BUV scatter plate.

Another possible source of degradation is through a surface cratering by micro meteorite impacts. The estimated particle flux for the 1100 km circular Nimbus orbit (Berg 1972) for 2π steradian at 90° to the spacecraft velocity vector is

$$\Phi = 2 \times 10^{-8} \text{ impacts/cm}^2\text{-sec}$$

The assumption of an average spherical particle mass of 10^{-13} g and a typical density of 1 g/cm^3 yields a particle radius of 0.3 μm. The crater r_c = 2r. The damaged area per impact, $A_D = \pi r_c^2 \approx 1.04 \times 10^{-8}$ cm^2. The number of

impacts/cm^2 yr $\approx$ 0.6/cm^2-yr which leads to a damaged area of 0.7×10^{-8} cm^2 which is completely negligible in relation to the typical MUSE sensor apertures of $\approx$ 0.4 cm^2.

The spectral behavior of the ATS-3 results which places an upper limit of about 650 nm on the wavelength at which loss in specularity is significant suggests that any droplets or other scattering irregularities formed are of very small size.

From experimental tests in the laboratory and uv observations on the Nimbus 3 and 4 spacecraft with the MUSE and BUV experiments the following have been observed.

(a) High energy electrons at MeV energies produce a change in transmittance (T) where

$$T \propto -\log \text{Dose } (e^-/cm^2)$$

(b) All forms of degradation can be represented by straight lines which show the effect of saturation through decreasing slope with increasing degradation.

(c) Transmittance loss from solar H Lyman alpha with time (t)

$$T \propto e^{-\alpha t} \qquad \alpha(t_1)/\alpha(t_2) = 120 \qquad t_2 > t_1$$

(d) Nimbus 4, BUV diffuse reflectivity (R)

$$R \propto e^{-\alpha t} \qquad \alpha(t_1)/\alpha(t_2) = 4.4$$

(e) Nimbus 4, MUSE (1216A)

$$T \propto e^{-\alpha t} \qquad \alpha(t_1)/\alpha(t_2) = 1.8$$

(f) Nimbus 3, MUSE (1216A)

$$T \propto e^{-\alpha t} \qquad \alpha(t_1)/\alpha(t_2) = 4.2$$

(g) Both the MUSE sensors and the BUV diffuser plate tend toward a cosine response with increasing time in orbit.

(h) The surfaces which were exposed directly to uv solar radiation experienced the greatest degradation.

It appears that the most likely source of uv degradation may be attributed to the deposition of μm size droplets resulting from spacecraft outgassing and the subsequent formation of permanent residues under the action of the uv solar radiation.

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